Carbon-Carbon Composite Radiator Development for the EO-1 Spacecraft

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ABSTRACT

The Carbon-Carbon Space Radiator Partnership (CSRP), an informal partnership of Government and industrial personnel, was formed to promote the use of Carbon-carbon composites (C-C) as engineering materials for spacecraft thermal management applications. As a part of this effort the partnership has built a structural radiator for the Earth Orbiter - 1 (EO-1) spacecraft. This radiator, using C-C facesheets with an aluminum honeycomb core, will demonstrate both the thermal and structural properties of C-C under actual service conditions as well as provide performance data from space flight. This paper will present results from the design of the radiator, the thermal/mechanical tests of the facesheet materials, and subcomponent test results on the C-C/Al honeycomb sandwich material.

The 29- by 28-inch radiator was designed to support two electronics boxes with a combined heat output of 60 watts maximum and a weight of 58 lbs. The analysis of the radiator design shows that the radiator constructed with 20-mil-thick facesheets of a P30-fiber-reinforced C-C from BFGoodrich is able to meet or exceed all the required thermal and mechanical requirements.

INTRODUCTION

The Carbon-Carbon Spacecraft Radiator Program (CSRP) was formed in August 1995. This informal partnership was formed to demonstrate that carbon-carbon (C-C) is now a viable engineering material (no longer considered exotic) for the spacecraft community because of its superb properties: lightweight, high tailorable thermal conductivity, chemical inertness and

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Figure 1. Membership list and photographs of CSRP members. Upper photograph shows the C-C radiator prior to vibration testing at GSFC with a portion of the dummy box masses attached.

others. CSRP members believe that C-C should be considered in the engineering trade space of spacecraft manufacturers but realize that databases of operational hardware do not exist. The members of CSRP have selected a structural electronics radiator as the demonstration article and plan a direct comparison to aluminum and organic composites under the same operational conditions. The radiators will be fabricated and will undergo extensive ground testing. A listing of the membership as well as two photographs that show most of the members is shown in figure 1. In addition to the demonstration articles, the partnership has also decided to take advantage of flight opportunities as they come available. The first flight opportunity the partnership has responded to was to build a structural radiator for the EO-1 spacecraft.

The Earth Orbiter-1 (EO-1) is the first of a series of earth orbiting missions for the NASA's New Millennium Program. This mission will validate a number of revolutionary technologies that will provide Landsat follow-on instruments with increased performance at lower cost. The primary payload (one of eight advanced technologies) is an Advanced Land Imager (ALI) instrument. Once on orbit, EO-1 will provide 100-200 paired scene comparisons between ALI and the Landsat 7 imager, ETM+. Such a comparison will validate the suitability of the multispectral capability of the ALI. EO-1 is scheduled (as of April 1998) to launch May 28, 1999.

Three equipment radiators were designed, built and tested (one flight, one backup and one for destructive testing). In addition, a spare Carbon-carbon composite (C-C) facesheet was characterized thermally and mechanically. The radiators were designed to meet the requirements of the bay-four radiator for the EO-1 spacecraft (figures 2 and 3). The 29 x 28 inch radiator was

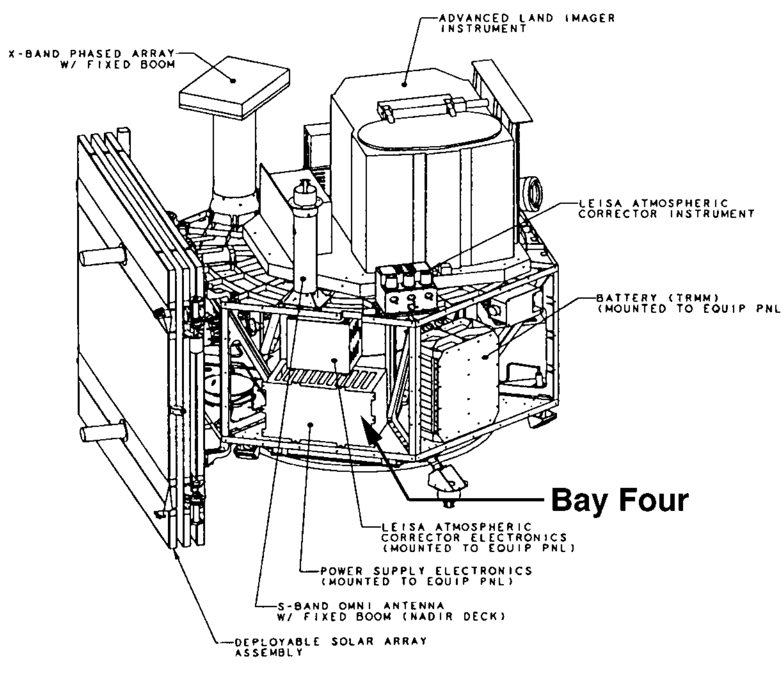

Figure 2. Layout of EO-1 satellite, highlighting bay four.

designed to support two electronics boxes and a total maximum heat output of less than 60 watts. The radiator was constructed using two approximately 0.020-inch thick C-C facesheets bonded to both sides of an aluminum honeycomb core for a total panel thickness of 1 inch. The properties used for the design of the radiator were estimated using a database[1] developed from previous C-C programs encompassing a wide variety of C-C composites. The thermal and mechanical tests carried out in this study were used to verify the facesheet and sandwich property values used in the mechanical models of the radiator.

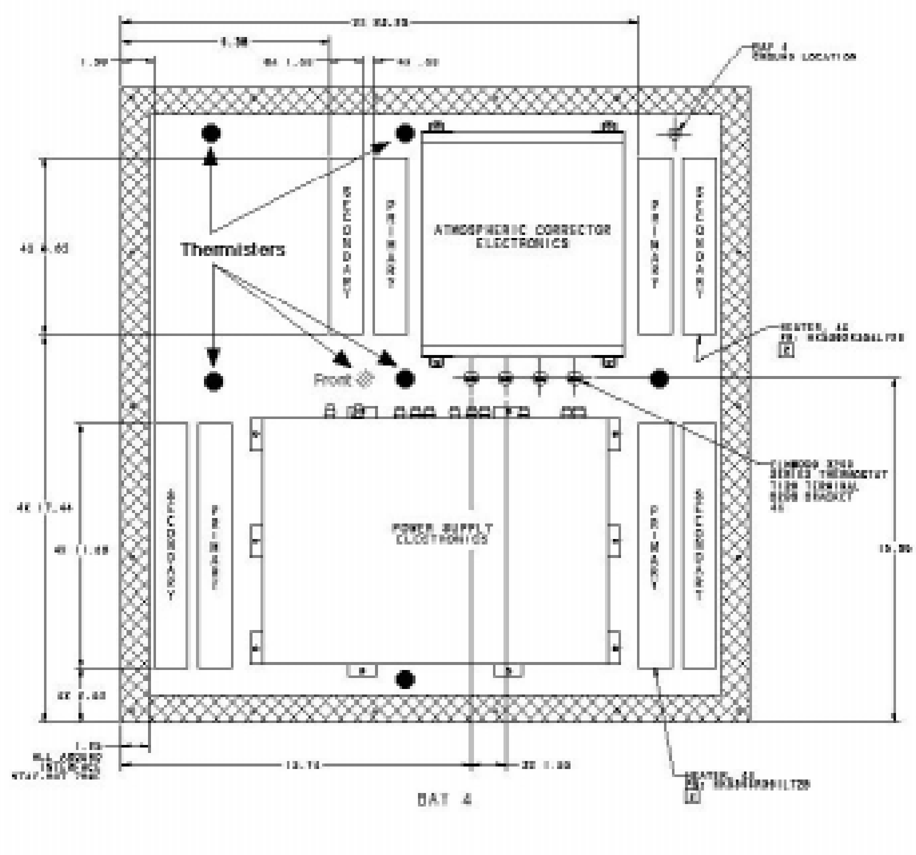

Figure 3. Layout of boxes, thermisters and inserts on C-C radiator.

FACE SHEET FABRICATION AND CHARACTERIZATION

The C-C facesheet tested was one of 9 identical facesheets fabricated by BFGoodrich[2] under a Navy contract. The facesheet was constructed as a 30-inch square panel using 2-ply fabric made with 2K-tow, P30 fiber, in a 1:1 5-H/S fabric. The fabric was laid up to provide quasi-isotropic reinforcement. Due to issues involving the width of the fabric it was necessary to offset the principle fiber directions 22.5° from the edges of the panels. The panel was pre-pregged using BFGoodrich's Hi-K process and densified using chemical vapor infiltration (CVI)

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[1] Sullivan, B. J.; Jones, G. F.; Buesking, K. W.; Dunn, M. J.: Carbon-Carbon Spacecraft Radiator Program: Material Trade Study and Detailed Design Tasks. Unpublished report for the Air Force Materials Laboratory, prepared under contract F33615-92D-5000/0069, Anteon subcontract 96-50000-69-1.

[2] BFGoodrich Company, Santa Fe Springs, CA.

carbon. The as-processed panel is shown in figure 4. The C-C facesheet material was evaluated for thermal conductivity, tensile strength and modulus, compression strength and modulus, interlaminar shear strength, interlaminar tensile strength, in-plane shear strength, bearing strength, and in-plane thermal expansion. BFGoodrich cut the facesheet into smaller sub-panels, designated A through F, which were shipped to NASA Langley. Sub-panels D and E were cut in half lengthwise at Langley and glued[3] together to achieve a double thickness sheet. The long direction of each panel was designated the 0° direction.

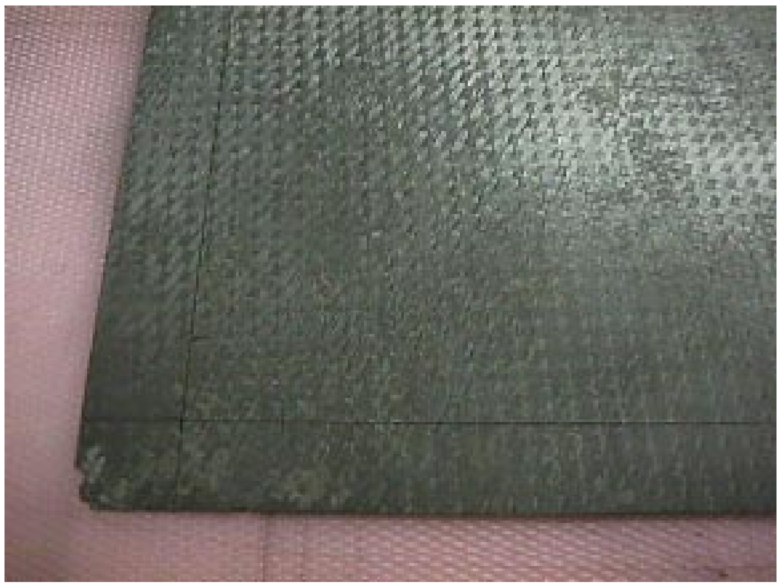

Figure 4. Carbon-carbon composite facesheet prior to trimming.

THERMAL CONDUCTIVITY TESTING

Thermal conductivity test specimens were cut from sub-panel A. Six 0.25- by 6.0- by 0.22-inch specimens were cut in both the 0° and 90° directions. One half the specimens were sent to Lockheed Martin Astronautics and forwarded to TPRL[4] and one half to NASA GSFC[5] for testing.

The samples submitted to TPRL were tested using the Kohlrausch method. The Kohlrausch method involves the determination of the product of the thermal conductivity "λ" and the electrical resistivity "ρ." Since the electrical resistivity is measured at the same time as the product of the resistivity and conductivity, λ can be calculated. The method involves passing constant direct current through the specimen to heat the sample while the ends are kept at constant temperature. Radial heat losses are minimized by an extenal heater whose center temperatures are maintained at the sample's midpoint temperatures and whose ends are also

[3] EA 934 NA, Hysol Aerospace products, Dexter Aerospace Materials Division, Pittsburg, CA.
[4] Thermophysical Properties Research Laboratory, West Lafayette, IN.
[5] National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, MD.

cooled by water or liquid nitrogen. Thermal conductivity values accurate to within ±5% are obtained by the Kohlrausch method and all measured quantities are directly traceable to NIST standards.

TPRL tested two of the six specimens. The results for sample TC-5 (90° direction) are given in Table I and the results for sample TC-11 (0° direction) are listed in Table II. The conductivity of the TC-11 (0°) sample is about 2% greater than the conductivity of the TC-5 (90°) sample. The resistivity of the TC-5 (90°) sample is around 1.5% greater than the resistivity of the TC-11 (0°) sample. Complete results are listed in reference 1.

TABLE I. Sample TC-5 (90° Direction) Thermal Conductivity

Temperature, °C	**Conductivity, W/m·K**	**Resistivity, microhms·cm**
41.3	213	562
51.3	214	554
75.7	209	537
97.6	205	525
121.6	198	513
153.5	193	500
172.2	191	493
197.7	186	484
223.5	180	477
251.9	175	470
282.9	170	463

TABLE II. Sample TC-11 (0° Direction) Thermal Conductivity

Temperature, °C	**Conductivity, W/m·K**	**Resistivity, microhms·cm**
51.4	215	546
72.4	213	532
95.9	209	519
119.3	202	507
144.6	197	496
168.5	195	487
193.0	190	479
216.8	185	472
239.6	180	466
263.6	175	460

The samples submitted to GSFC were used to measure the thermal diffusivity and specific heat of the composite facesheet. The thermal conductivity was calculated from thermal diffusivity (γ), specific heat (C_p), and density (d) using the following equation:

$$K = \gamma \cdot C_p \cdot d \qquad [1]$$

Thermal diffusivity was measured using the Angstrom's temperature wave method. A Peltier junction is used to generate a periodic heat wave along a specimen. Two thermocouples are used to measure the decay in amplitude and phase shift of the heat wave as it travels along the sample. These two parameters are used to calculate themal diffusivity (ref. 2). The spacing between the thermocouples was nominally 7 cm and the frequency of the heat wave was 0.03 Hz.

The thermal diffusivity of 2 specimens was measured in the 0°-ply direction and in the 90°-ply direction for the others. The measured values from the 4 specimens did not vary much and were compiled together Thermal diffusivity measurements were only possible up to about +40 °C for these specimens. The specific heat was measured using a TA Instruments DSC 910 Differential Scanning Calorimeter. The density of this material was measured to be 1.78±0.01 g/cm^3. Table III is a summary of the thermal diffusivity measurements and conductivity calculationsfrom 4 carbon-carbon composite specimens.

TABLE III. In-Plane Thermal Diffusivity and Conductivity Results

Temperature, °C	Thermal Diffusivity, cm^2/sec	Thermal Conductivity, W/m-K
-20	1.7±0.3	202±39
-10	1.7±0.3	205±36
0	1.6±0.2	207±33
+10	1.6±0.2	208±27
+20	1.5±0.2	208±25
+30	1.4±0.2	208±22
+40	1.4±0.2	206±21

The measurements made at TPRL and at GSFC show good agreement with each other. At 40°C, the one temperature that the two sets of measurements have in common, the results were 206±21 W/m·K by GSFC and 213±11 W/m·K by TPRL. The values are well within the error bands for the measurements. The measurements are also close to the trade study approximation of 220 W/m·K for this material. Figure 5, shows a summary plot of the thermal conductivity measurements from the GSFC and TPRL.

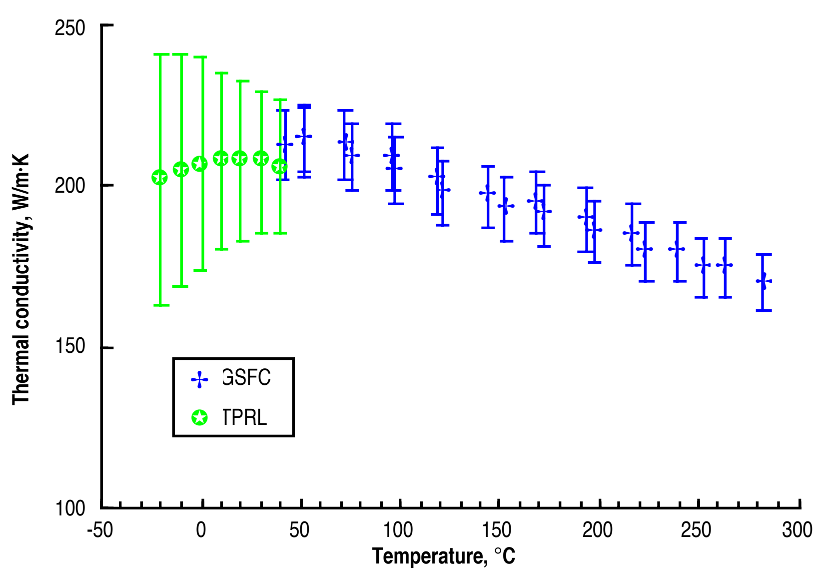

Figure 5. Combined thermal conductivity measurements from GSFC and TPRL for the C-C composite facesheet material. The bars show the estimated errors of the measurements.

MECHANICAL TESTING

A summary of the mechanicaltest results is shown in Table IV. Also included in Table IV are data for an 8-ply material that was produced by BFGoodrich using the same fibers, fabric, matrix and heat treatments as the material in this study. The major difference between the two composites was the number of plies (an 8-ply composite versus the 2-ply composite used for the radiator) and the directional lay-up (0/90 for the 8-ply and 22.5/112.5 for the 2 ply).

The average tensile strength was 16.7 ksi and the average modulus was 12.6 Msi. The tensile strength and modulus were the only properties measured in this study that were significantly different from projected by the trade study (approximately 30 ksi, 18 Msi). In addition, the tensile data had a large amount of scatter. One possibility for the low strength is that the short length of the fibers in the gage section, maximum of 1.3 inches, is affecting the measured strengths and moduli values. Although short effective fiber length might give a lower average strength, the large amount of scatter was not anticipated. Future testing of specimens cut in the 22.5° direction should help to clarify the issue.

The average compression strength value for the 0° direction was 14.3 ksi and 13.6 ksi for the 90° direction. The compression strength projected in the trade study was 13 ksi, very close to the measured values. The compression modulus values were 14.7 Msi in the 0° direction and 12.8 Msi in the 90° direction. The measured compression modulus is slightly below that projected in the trade study, 16 Msi. However, because of the difficulty of trying to attach the clip gage to a very thin specimen edge and the short gage length (0.5 inch), the scatter in the data was higher than usual. Due to the high scatter, a statistical test was run to determine if there was a significant difference in the modulus values measured between the 0° and 90° directions and among the 0°, 90° and the projected values The statistical test showed no significant difference between the modulus values for the 0° and 90° directions at an alpha of 0.05. There was also found to be no significant difference between the measured modulus value for the 0° direction and the projected value of 16 Msi at an alpha of 0.05. However, there was found to be a difference between the modulus value for the 90° direction and the projected value at an alpha of 0.05 but not at an alpha of0.025.

The interlaminar shear strength was measured using a double-notch shear specimen. The initial trial sample failed in compression at the thin web of material next to the gage section. After this experience, tabs were glued on the remainder of the test specimens to carry the load into the shear section. This resulted in four successful shear failure tests. In the majority of the other cases the shear failure occurred between the plastic tab and the C-C composite. The average interlaminar shear strength value was 1.4 ksi. This is a good value for most types of C-C composites but below the 2.5 ksi typically measured for CVI-densified C-C.

The interlaminar tensile strength (ILT) was measured using a flatwise-tensile test using 0.75-inch square specimens. All specimens failed between the two C-C plies. The average ILT strength value was 1.3 ksi. This value is higher than was measured for the 8-ply composite and may be related to betterpenetration of the CVI matrix due to the thinness of the composite.

The in-plane shear strength was measured using the v-notch Iosipescu method. The average in-plane shear strength value measured was 13.7 ksi. Due to the thin nature of the composites it was found to be necessary to tab the specimens. The average shear strength value is significantly greater than the 10 ksi measured for the 8-ply material and the 9.5 ksi predicted by the trade study. The reason for this is probably due to the fact that all the fibers help to resist the load applied to the specimen due to the 22.5° angle of the lay-up. In typical quasi-isotropic lay-ups tested in the 0° direction some of the fibers would have been parallel to the shear (0°) direction and would have provided no reinforcement.

The bearing strength was measured using the tensile bearing method. All specimens had 0.5-inch holes. In the edge-bearing specimens the centers of the holes were placed 0.5 inch from the edge of the specimens. This was to simulate the distance between the outside fasteners and the edge of the radiator panels. In the center-bearing specimens the hole centers were moved to 1.5 inches from the edge to simulate a fastener in the interior of the panel. The specimens were cut in either the 0° or 22.5° direction. At the time the radiator preliminary designs were completed there was a concern that the 22.5° lay-up of the fabric could result in an inadequate level of shear strength near the panel edges. This lack of strength would have necessitated applying a doubler to the edge of the actual EO-1 radiator panels. To simulate the presence of a doubler, two panels were sliced in half and bonded back together to give a doubled thickness panel. Unfortunately the glue was applied too thickly and resulted in specimens with too much glue between the C-C plies.

TABLE IV. Mechanical Test Data for 2-ply EO-1 C-C Facesheet and Comparable 8-ply Material

Test	Average value	St. Dev. value	No. of samples	Glue layer mils	Failure mode	8-ply material	St. Dev.
Tensile							
strength (0°), ksi	16.7	6.8	9			30.6	1.3
modulus (0°), Msi	12.6	3.2	10			19.6	0.9
Compression							
strength (0°), ksi	14.3	1.3	9			12.7	0.5
modulus (0°), Msi	14.7	4.2	8			16.1	2.2
strength (90°), ksi	13.6	1.0	8				
modulus (90°), Msi	12.8	3.4	8				
Interlaminar tensile strength, ksi	1.3	0.1	10			0.8	0.1
Interlaminar shear strength (DNSS), ksi	1.4	0.4	4			2.4	0.1
In-plane shear strength (Iosipescu), ksi	13.7	1.0	4			9.6	0.3
Bearing strength single							
(0°, near edge), ksi	13.3	0.6	3		Crush		
(22.5°, near edge), ksi	12.5	0.9	3		Crush		
(0°, center) , ksi	12.6	0.8	3		Crush		
(22.5°, center) , ksi	11.4	0.5	3		Crush		
Bearing strength double							
(0°, near edge) , ksi	11.2	0.5	2	39	Shear		
(22.5°, near edge) , ksi	12.8	1.0	3	38	Shear		
(0°, center) , ksi	13.1	0.7	3	28	Crush		
(22.5°, center) , ksi	13.8	3.4	3	45	Crush		

The average bearing strength values of the single composites in the 0° and 22.5° directions in both center and edge tests was 12.5 ksi. The average bearing strength values of the double composites in the 0° and 22.5° directions in both center and edge tests averaged 12.1 ksi. All the specimens failed in crushing except for the doubled edge specimens that failed in shear. It appeared that during the test of the doubled edge specimens that the glue layer failed first followed by the C-C composite. It was concluded from the good strength values and the lack of shear failure in the single edge specimens that the doubling of material was not needed in the final radiator composites.

IN-PLANE THERMAL EXPANSION

The thermal expansion of the specimens was measured in the 0° and 90° directions using an optical interferometry system. The expansion of the specimens was measured between 120°C and -100°C (250°F to -150°F). Over this temperature range the expansion was fairly linear. The coefficient of thermal expansion (CTE) was calculated using a linear fit of the data between 120°C and -100°C. Figure 6 shows the overlap and linearity of the data. The average CTE in the 0° direction was -1.23 x 10^{-6}/K and -1.26 x 10^{-6}/K in the 90° direction.

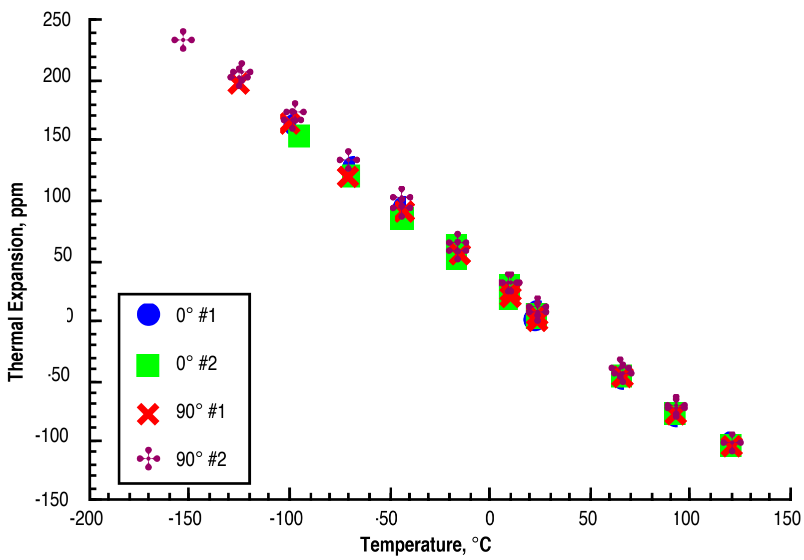

Figure 6. Thermal expansion versus temperature for EO-1 C-C facesheet material.

HONEYCOMB PANEL ASSEMBLY AND TESTING

The C-C facesheets were joined to 2-lb/ft^3-aluminum honeycomb by Lockheed Martin Vought Systems to make the sandwich panels. The procedures used were similar to those for the construction of honeycomb-reinforced aluminum facesheet panels and will not be covered in this paper. Three types of inserts were used: a 0.250-28 THD insert, a #10-32 THD insert and a blank insert. The blank insert was drilled through to provide holes for the attachment bolts that secure the radiator panel to the frame of the spacecraft. Figure 7, shows one of the panels being prepared for insertion of the potting compound along the outside insert locations. Figure 8, shows the edge of the panel after consolidation of the facesheets with the honeycomb core. The potting compound for the edge holes is clearly visible. The interior and exterior surfaces of one of the radiator panels, after installation of the inserts and the application of the silver Teflon tape, are shown in figures 9 and 10.

Figure 7. Radiator panel prepared for insertion of potting compound in edge loactions.

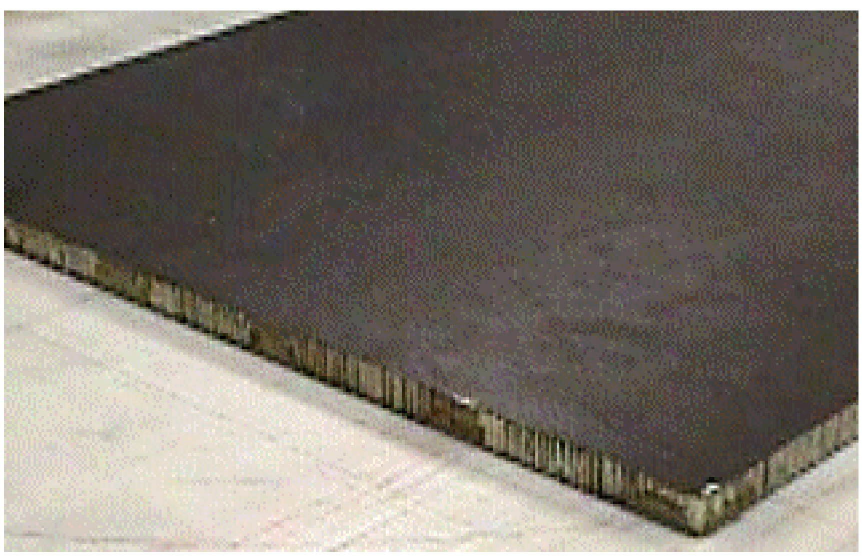

Figure 8. Edge of C-C radiator panel prior to installation of inserts.

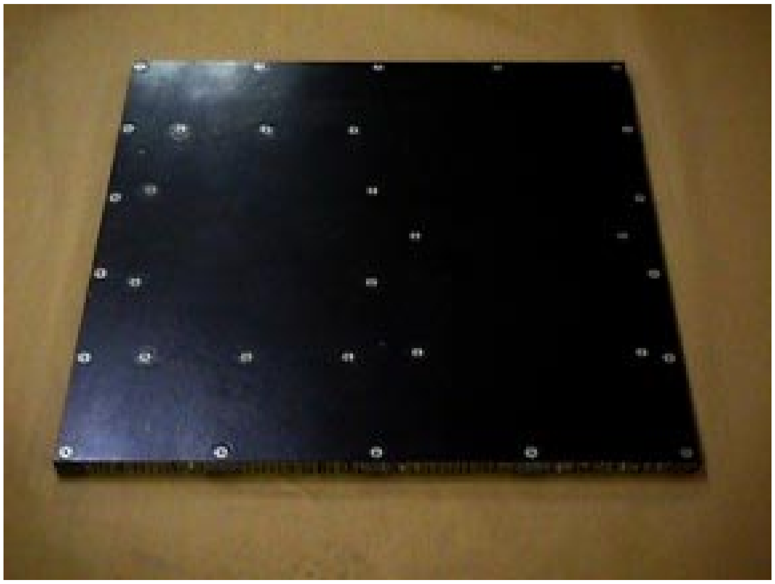

Figure 9. Interior surface of radiator panel after insertion of attachment inserts.

Figure 10. Exterior surface of radiator panel after installation of the silver Teflon tape.

The mechanical tests planned for the Honeycomb panel include insert pullout, flatwise tension, pin bearing-blind inserts, and facesheet/core shear. Figure 11 shows the location of the test specimens from the panel. The flatwise tensile and facesheet/core shear test specimens were cut from the clear areas of the panel.

The insert pullout test was conducted by Lockheed Martin Astronautics. The inserts tested had a diameter of 0.56 inches. Table V lists the test results. The minimum pullout load was 550 lbs. and the maximum was 1276 lbs. The large size of the plugs pulled out reflected the size of the regions around the inserts that had been filled with potting compound. The design load for pulling out the inserts is about 50 lbs. Even the weakest specimen had a factor of 10 over capacity in the normal direction. Figure 12 shows a photo of specimen InPul-4 after failure. The large region of material pulled out with the insert is clearly visible.

TABLE V. Results of the Sandwich Insert Pullout Test

Specimen ID	Specimen Dimensions, in.			Maximum Load, lbs.	Comments
	Thickness	Width	Length		
InPul-1	0.988	3.998	4.000	550	1-in. dia. plug region
InPul-2	0.992	3.996	4.000	1276	>1-in dia. plug region
InPul-3	0.994	3.998	3.999	607	>1-in dia plug region
InPul-4	0.995	3.996	4.004	980	>1-in dia plug region

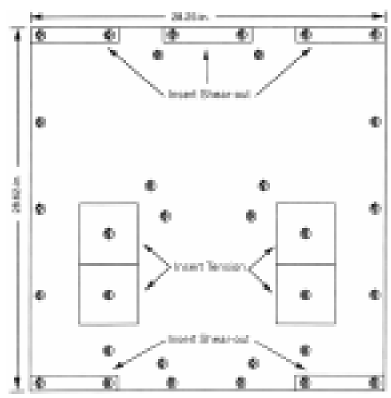

Figure 11. Layout of test specimens from the radiator panel for destructive testing.

Flatwise tensile tests were conducted on the honeycomb sandwich using ASTM Standard C297-94. The results of the test are given in Table VI. The average measured strength was 429 lbs. with a standard deviation of 27 lbs. The failures were in the bond line at the aluminum honeycomb core and C-C interface.

Insert bearing tests were conducted using the configuration shown schematically in fgure 13. Each specimen was prepared with the e/d (edge distance to insert diameter) ratio of 1.0 (insert diameter 0.50-in., specimen width - 1.0-in.). The average bearing load was 336.3 lbs.

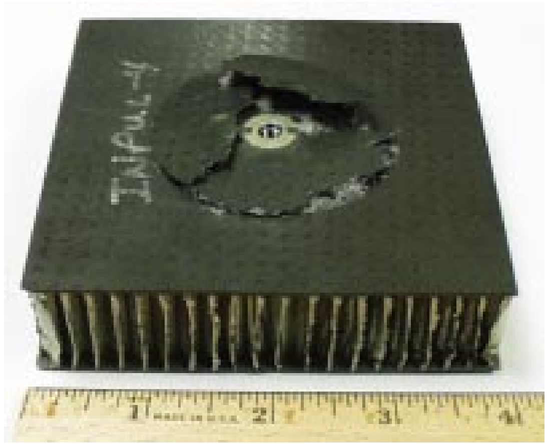

Figure 12. Post-test photo of insert pull out test specimen InPul-4.

TABLE VI. Results of the Flatwise Tensile Testing

Specimen ID	Thickness, in.	Length , in.	Width in.	Max. Load, lbs.	Ultimate Strength, psi
FLTEN-1	0.990	1.500	1.502	992	440
FLTEN-2	0.990	1.501	1.499	945	420
FLTEN-3	0.989	1.498	1.503	1001	445
FLTEN-4	0.990	1.503	1.498	970	431
FLTEN-5	0.992	1.503	1.501	979	434
FLTEN-6	0.991	1.503	1.502	836	370
FLTEN-7	0.991	1.503	1.502	983	435
FLTEN-8	0.992	1.503	1.503	1037	459
			Average	9679	429
			Std. Dev.	59	27

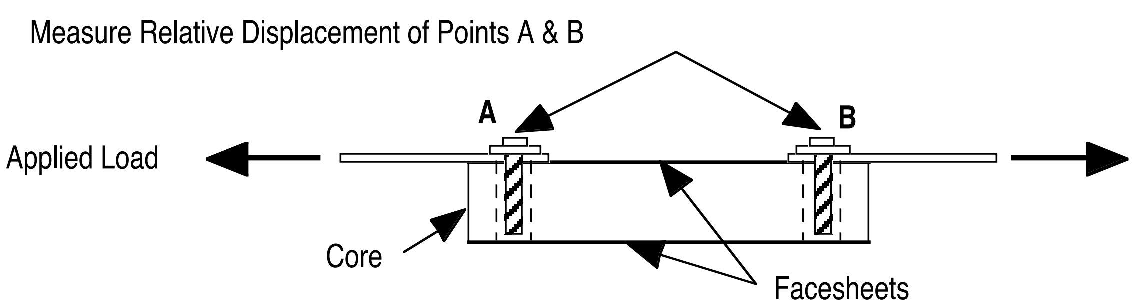

Figure 13. Schematic of pin bearing test configuration.

TABLE VII. Results of the Insert Bearing Tests

Specimen ID	Thickness, in.	Width, in.	Max Load, lbs.
BNG-1	0.990	1.0	401.9
BNG-2	0.990	1.0	322.6
BNG-3	0.990	1.0	284.5
		Average	336.3
		St. Dev.	59.9

with the standard deviation of 59.9 lbs. The large scatter was primarily due to the core fill diameter around each insert varying from 0.8 to 1.0-in. The failure was tensile in nature as the insert the core fill acted as a large effective insert to an applied tensile load. The calculated average failure stress value of approximately 17 ksi is quite comparable with the tensile strength of the 0.020-in. P30X/C laminate.

DISCUSSION AND CLOSING REMARKS

The results of the tests show that the thin 2-ply composites performed essentially as predicted by the trade study and similar to 8-ply materials fabricated using similar procedures. The only exception to this was the low and widely scattered tensile strength and modulus values. This may reflect the specifics of the composite lay-up and the geometry of the tensile test and not reflect a true difference in tensile strength between the projected value and the measured value.

The radiator panel constructed using the C-C facesheets with the aluminum honeycomb core also performed well, with the insert pullout strengths being well above that required for the application. Based on the trade study, and the mechanical and thermal properties measured in this study the carbon-carbon composite radiator panel design was found to be more than adequate for the EO-1 bay four radiator panel.

The flight radiator and backup radiator were delivered to NASA Goddard and have successfully completed thermal/vacuum and vibration testing (not described in this paper). The panels were delivered to the EO-1 spacecraft integrator, Swales Aerospace, on May 19, 1998.

The final point to be made regarding the suitability of C-C radiators for use on future spacecraft concerns cost and availability. Table VII shows the approximate cost associated with the design, fabrication, and ground testing of the three panels for the EO-1 spacecraft. The tasks include non-recurring costs that would not need to be repeated for future radiators if a similar design were used. The radiator integration task includes approximately $22 K of non-recurring costs. The time for total production (fabric to tested flight unit) was about 10 months but could be optimized to 6 months using current production technology. It is predicted that the total cost would be $283 K for an additional set of C-C radiator panels using the EO-1 design.

TABLE VII. CSRP EO-1 C-C Radiator Cost Summary*

1	**	Material and design trade study	$80 K
2		C-C facesheet fabrication	$90 K
3	**	Radiator integration	$140 K
4	**	Material property tests	$25 K
5		Flight unit thermal/vac test	$50 K
		Total	**$385 K**

* Doesn't include program management and travel costs

** Includes nonrecurring costs

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1 Groot, H; and Taylor, D. L.: *Thermophysical Properties of P30X/C EO-1 Specimens, A Report to Lockheed Martin Astronautics*. TPRL 1967, January 1998.

2 Touloukian, Y.S.; Powell, R.W.; Ho, C.Y.; and Nicolaou, M.C.: *Thermal Diffusivity – Vol. 10 of Thermophysical Properties of Matter -- The TPRC Data Series*, pp. 28a-37a, IFI/Plenum Data Corp., NY, 1973.